A Theoretical Analysis of Steady-State Photocurrents in Simple Silicon Diodes

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ABSTRACT

Funneling under steady-state conditions is investigated, because this problem is simple enough to be treated rigorously and provides some qualitative insight into the more difficult transient problem,

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Funneling occurs when carriers are generated in sufficient quantity near a p-n junction depletion region (DR) that the DR becomes flooded and partially, or completely, collapses. Some or nearly all voltage normally across the DR is now across a substrate or epi layer, resulting in an electric field that enhances charge collection. This can occur under steady-state as well as transient conditions. The two types of conditions have some common qua] itative characteristics, and concepts derived for the simpler steady-state problem can add physical insight into the more difficult transient problem,

As shown in Fig. 1 for an n +/p device, the simple silicon diode considered consists of a uniformly doped substrate between a p-n metallurgical junction (MJ) and an ohmic contact (electrode). The p-n junction depletion region boundary (DRB) separates a strong space-charge region (the DR) from a quasi-neutral region. The. simpler term "substrate" will refer to the quasi-neutral region from now on. Steady-state photogeneration occurs in the DR and/or substrate, and the generation rate density is assumed to be a known function (called the photogeneration rate function) of the spatial coordinates. The full paper gives results for the n +/p and p+/n diodes. The HRR and AR shown in Fig. 1 are discussed later.

The nonlinear drift-diffusion equations are simplified by assuming constant nobilities in the substrate (although electric field dependent mobilities are used in the DR) and neglecting recombination in the substrate and DR interiors. A novel and rigorous mathematical analysis then produces approximate solutions for arbitrary three-dimensional substrate geometries. Solutions are expressed in terms of equilibrium resistance (the resistance between electrode and DRB that would occur if there were no excess carriers), diffusion currents (predicted by the linear diffusion equation with simple boundary conditions), and another nameless quantity derived from the photogeneration rate function. These quantities implicitly contain the required geometric data and substitute for physical dimensions in the formal solutions (e. g., instead of specifying a length and area, we specify an equilibrium resistance). The advantage of this approach is that the equations are geometrically covariant, in the sense that the same equations are used for all geometries. Final numerical calculations are geometry specific and straight- forward in one dimension. The three-dimensional case is made tractable by confining our attention to a special family of photogeneration rate functions, constructed so that all relevant functions of the spatial coordinates can be expressed as functions of a suitably chosen generalized coordinate (fitting is necessary if a given generation rate function does not belong to the family). Some mathematical manipulations then show how numerical esti mates can be obtained from the same calculations that would be used in one dimension. The user must provide an equilibrium resistance estimate and a fitting function representing photogeneration. All other calculations, including diffusion current estimates, are summarized in a "cook-book" recipe.

The present work finds that, during funneling, the ambipolar diffusion equation fails to provide a good approximation for the carrier density function. This is due to strong substrate electric fields. A more accurate equation is provided for quantitative calculations, but a simpler "generalized ambipolar approximation" is useful for visualization, and is described the following way.

The substrate divides into two subregions (Fig. 1). Adjacent to the electrode is a high-resistance region (HRR) characterized by a small excess carrier density and strong electric field. This region forms because funneling-induced substrate fields drive minority carriers up from the electrode. There are virtually no replacement carriers supplied by the electrode, so the region is depleted of minority carriers. Quasi-neutrality insures that the region is also depleted of excess majority carriers. The conductivity is much less than in the high-density region above the HRR, so nearly all the substrate voltage drop is across the HRR. The region above the HRR is called the ambipolar region (AR) and is characterized by a high carrier density and weak electric field. The ambipolar diffusion equation applies to this region, but boundary conditions must be modified to account for the ambipolar region boundary (ARB) that separates the AR from the HRR.

The HRR controls substrate resistance, while the ARB affects carrier density in the AR as if the electrode were moved closer to the DRB. Furthermore, a strong HRR electric field can drive nearly all minority carriers to the DRB. Replacing the electrode with a high-low junction, which blocks the minority carrier current, will have little effect (when funneling is sufficiently strong), because this current is blocked anyway. The device is in saturation during sufficiently strong steady-state funneling, i.e., nearly all liberated charge is collected. This is an important distinction between the steady-state and transient cases. Funneling is strong only part of the time at most for the latter case, and collected charge can be less than the total amount liberated.

Because the DR has a built-in potential, funneling does not require the diode to be reverse-biased. The effect of bias voltage can be seen by looking at an I-V curve corresponding to a given generation rate. Fig. 2 shows such a curve for a one-dimensional diode with five microns between electrode and MJ, a p-type doping density of 8×10^{14} cm^{-3}, a n-type doping density of 1.0×10^{20} cm^{-3} (implying a 0.871 volt built-in potential) and a uniform generation rate of 1.25×10^{25} cm^{-3}s^{-1}. This generation rate results in the carrier density typically being at least an order of magnitude greater than the doping density, which may be representative of some transient funneling cases. It is seen that saturation is reached even at some negative voltages (solar cell operation). A PISCES prediction is shown for comparison. The model used PISCES default values for relevant material constants, but the two results are otherwise independent in the sense that the model contains no "fudge factors" or fitting parameters that would improve agreement with PISCES. PISCES includes a variety of second-order effects (several types of recombination, and mobility depends on everything), so the good agreement indicates that the simplified drift-diffusion equations are adequate for this case. The "classical" curve is derived from the classical analysis that does not include the effect of electric field on minority carriers. It was found (not shown here) that the model and classical curves are more nearly the same if the generation rate is reduced by two orders of magnitude, indicating that funneling is not important at this reduced rate.

A plot, corresponding to V= 1 volt in Fig.2, of electron density with distance from MJ is shown in Fig.3, where the HRR and AR are identified. The PISCES result places the DRB closer to the MJ than the model prediction (it is not clear why) and this shift accounts for most of the difference between the two curves in Fig.3. The DRB and ARB locations shown in the figure are model predictions. The substrate voltage drop for this configuration is 1.62 (PISCES) or 1.63 (model) volts, implying funneling, under steady-state conditions. About two tenths of a volt is across the AR, with the remainder across the HRR, consistent with the statement that most substrate resistance is in the HRR.

The effect of carrier generation location is also interesting. The Fig.2 model curve is replotted in Fig.4, together with an I-V curve produced when all carrier generation is 2.5 microns above the electrode (more than 1 micron below the unperturbed DRB for biasing voltages up to 0.5 volts). The total generation below the MJ is the same for both cases. The two curves are indistinguishable, i.e., it makes no difference (to the I-V curve) whether carriers are generated uniformly in the DR and substrate, or all generation is in the substrate midway between the MJ and electrode. Funneling occurs in both cases. For the latter case, carriers generated below the DR must first diffuse to the DR to get the funneling process started. Once there, the DR partial] y collapses and a substrate electric field is created. This field drives more minority carriers to the DR and the funneling process becomes self-sustaining. It is clear that funneling can be induced at a distance, i.e., carriers need not be generated inside of the DR. Fig. 4 also shows the case where all carrier generation is 1 micron above the electrode. Classical theory predicts a comparatively weak current for this case, because carriers are general ed close to the electrode where they recombine. The model shows that funneling is now diminished, but still present and the current is much larger than predicted by classical theory.

Although we can expect some differences between steady-state funneling and transient funneling produced by an ion track, we can also expect some similarities. If the ion track is not long enough to reach the electrode, we can expect an HRR below the track, with an electric field inhibiting the downward flow of minority carriers. This is seen in some transient simulation results showing an absence of downward diffusion. If the track does reach the electrode, the lower end will have to be cleared away before an HRR can form. It seems reasonable to expect a large current during this time, unless the current is limited by external circuit resistance. We can also expect funneling to be induced at a distance, i.e., not requiring a direct DR hit. This is not predicted by existing transient models and is one of the most important conclusions of this work. The present work provides at least a qualitative understanding of multiple-bit single event upsets (SEUs) at normal incidence, and the ability of lasers to induce SEUS without a direct DR hit.

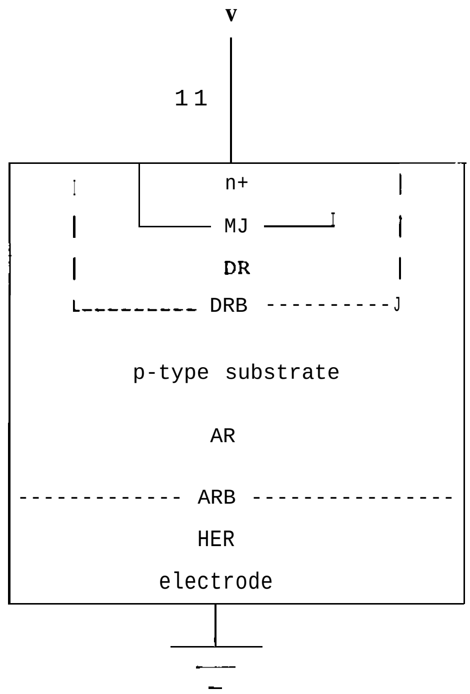

Figure 1: Qualitative sketch of an n+/p diode showing a metallurgical junction (MJ), a depletion region (DR) and boundary (DRB), an ambipolar region (AR) and boundary (ARB), and a high-resistance region (HRR). The current I is positive when directed downward.

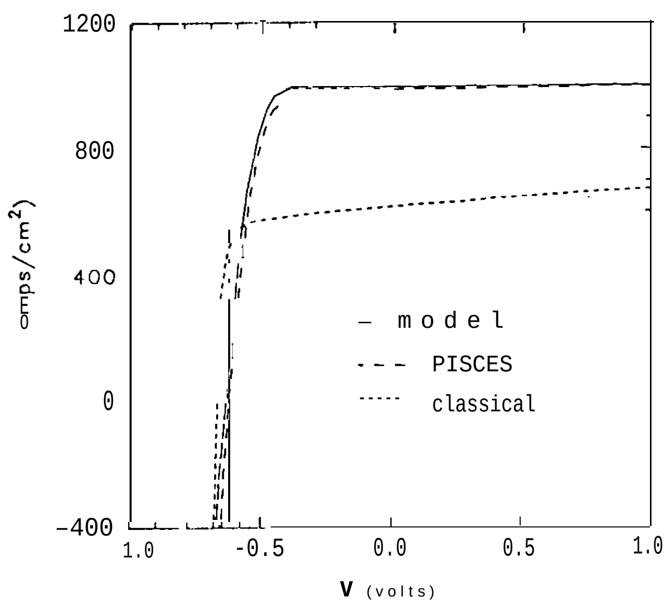

Figure 2: Comparison of I-V curve predictions for the same diode with a uniform carrier generation rate.

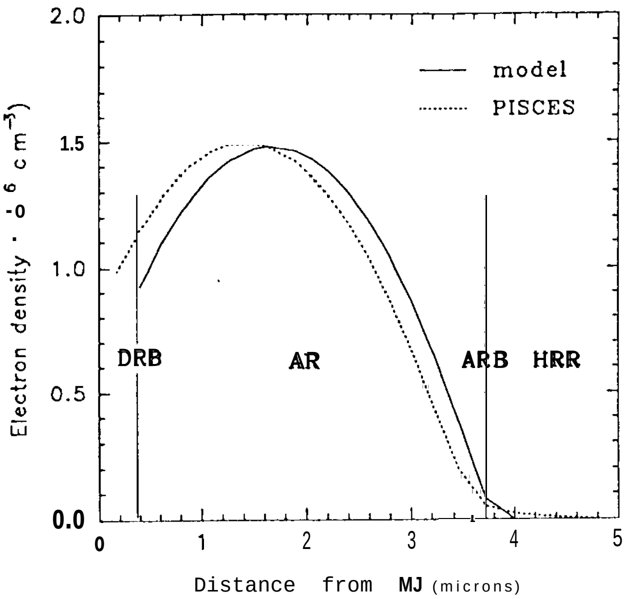

Figure 3: Comparison of electron density predictions for the same diode with a uniform carrier generation rate.

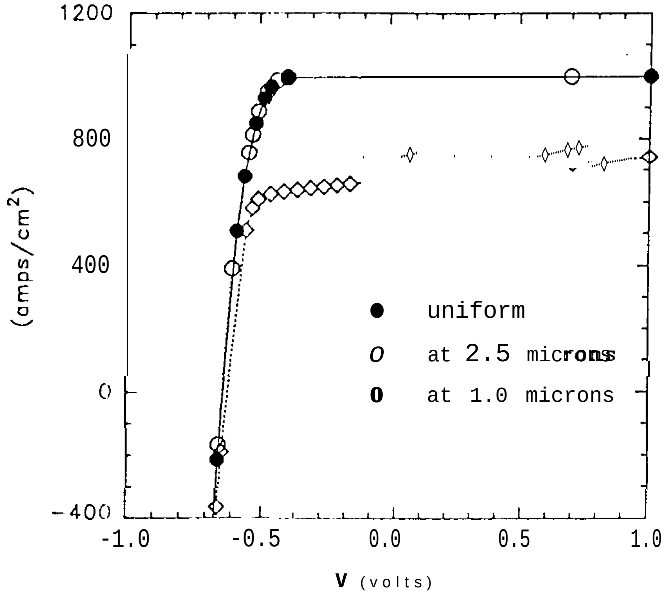

Figure 4: Comparison of I-V curves for different carrier generation locations. For one curve, generation is uniform. For the other two curves, all carriers are generated at the indicated distance above the electrode.